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# HIGH- $T_c$ SQUID APPLICATION IN MEDICINE AND GEOPHYSICS

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In our Laboratory a high- $T_c$  one-hole squid was built from  $Y_1Ba_2Cu_3O_{7-x}$  ceramics obtained by a standard procedure of solid state reaction [1]. The ceramics with critical current density  $J_c > 100 \text{ A/cm}^2$  was selected.

In the middle of  $10 \times 10 \times 2 \text{ mm}$  ceramics pellet a  $0.8 \text{ mm}$  hole was drilled in which superconducting loop of the squid was located. Between the hole and the edge of the pellet a cut was mechanically filed out with a bridge inside it connecting the superconducting ring. The bridge with characteristic size of  $10 \mu\text{m}$  must have the critical current  $I_c \approx 10 \mu\text{A}$  for the squid hysteretic parameter  $\beta = 2\pi L_S I_c / \phi_0$  to be less than  $(5 \div 10)$ . Here -  $L_S$  - quantum loop inductance,  $\phi_0$  - magnetic flux quantum. The squid is depicted in fig.1. In order to provide the mechanical stability  $Y_1Ba_2Cu_3O_x$  dielectric phase was used.

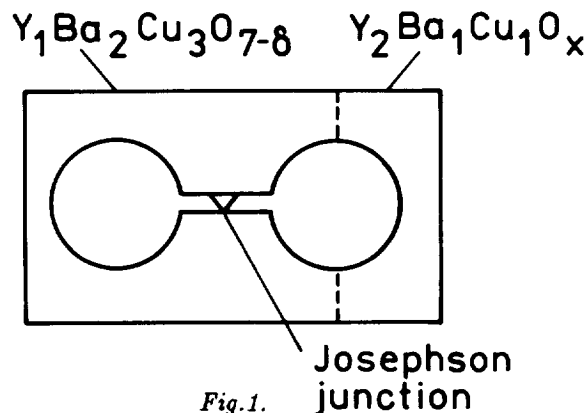


Fig.1.

In fig.2 a scheme of the magnetometer is presented. The squid - 1 was pumped, as usual, at high frequency ( $f_p \approx 20\text{MHz}$ ) by the rf-generator - 2 and was tested by the tank circuit  $L_T C_T$  - 3, inductively coupled with it which was tuned on resonant frequency -  $\omega_p$ . In order to obtain the maximum response the coefficient of coupling is chosen by the relation  $K^2 Q \approx \pi/2$ , where  $Q$  is the quality factor of the circuit. The circuit voltage is amplified by a low-noise rf-amplifier - 4 and is detected by an amplitude detector - 5. The detected signal is transformed by low frequency units - 6,7, which provide flux-locked regime to the magnetometer. All these units are completely identical to electronic units of low-temperature squids.

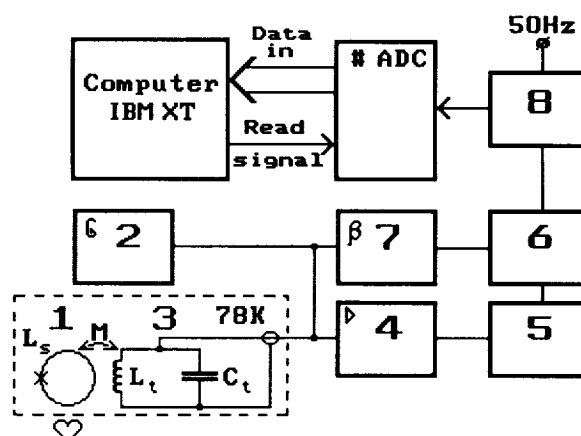


Fig.2.

### Main characteristics of the magnetometer

The squid inductance can be measured experimentally, by the method described before. The resonant frequency shift of the tank circuit, which arise influenced by the squid, the connection of the squid with this circuit and the squid inductance are evaluated:

$$L_S = I_0^2 C_T / \phi_0^2 (\omega_{p1}^{-2} - \omega_{p2}^{-2}),$$

where  $I_0$  - current value through the  $L_T$ , changing the squid flux on  $\phi_0$ ;

$C_T$  - tank circuit capacity;

$\omega_{p1}$  - tank circuit resonant frequency measured at a low pumping level when the contact remains superconductive and dissipative processes in the squid are not observed;

$\omega_{p2}$  - tank circuit resonant frequency measured at a high pumping level when Josephson contact is not superconducting.

The measurements have shown that at superconducting ring diameter of 0.8mm  $I_0 \approx (0.8 \pm 0.1) \mu A$ ,  $k \approx (0.15 \pm 0.01)$ ,  $C_T \approx (220 \pm 10) pF$ ,  $f_{p1} = (17.7 \pm 0.1) MHz$ ,  $f_{p2} = (17.35 \pm 0.1) MHz$  and squid self inductance  $L_S = (2.5 \pm 0.1) \times 10^{-10} H$ .

Spectral noise density dependence on magnetic flux  $\phi_N \approx 4.5 \times 10^{-4} \phi_0 / \sqrt{Hz}$ . The calculations give us energy resolution in the white noise region  $\epsilon = \phi_N^2 / 2L_S \approx 9 \times 10^{-28} J/Hz$ .

The calibration in the Helmholtz rings has shown the volt-oersted field period to be  $B_0 = 3.8 \times 10^{-10} T$ , knowing which one can easily obtain the estimate of the squid field sensitivity:  $\langle B_N \rangle = \langle \phi_N \rangle B_0 / \phi_0$ .

In fig.3 the spectral noise density on magnetic field of the magnetometer based on the high- $T_C$  ( $T=77K$ ) one-hole squid is shown (lower curve). It is evident that in the white noise region self field sensitivity is  $\sim 10^{-13} T/Hz^{1/2}$ . Thus, even today the high- $T_C$  squids are inferior only to the best low-temperature squids at  $T=4.2K$ . For comparison spectral noise density of the traditional magnetometers is given in fig.3.

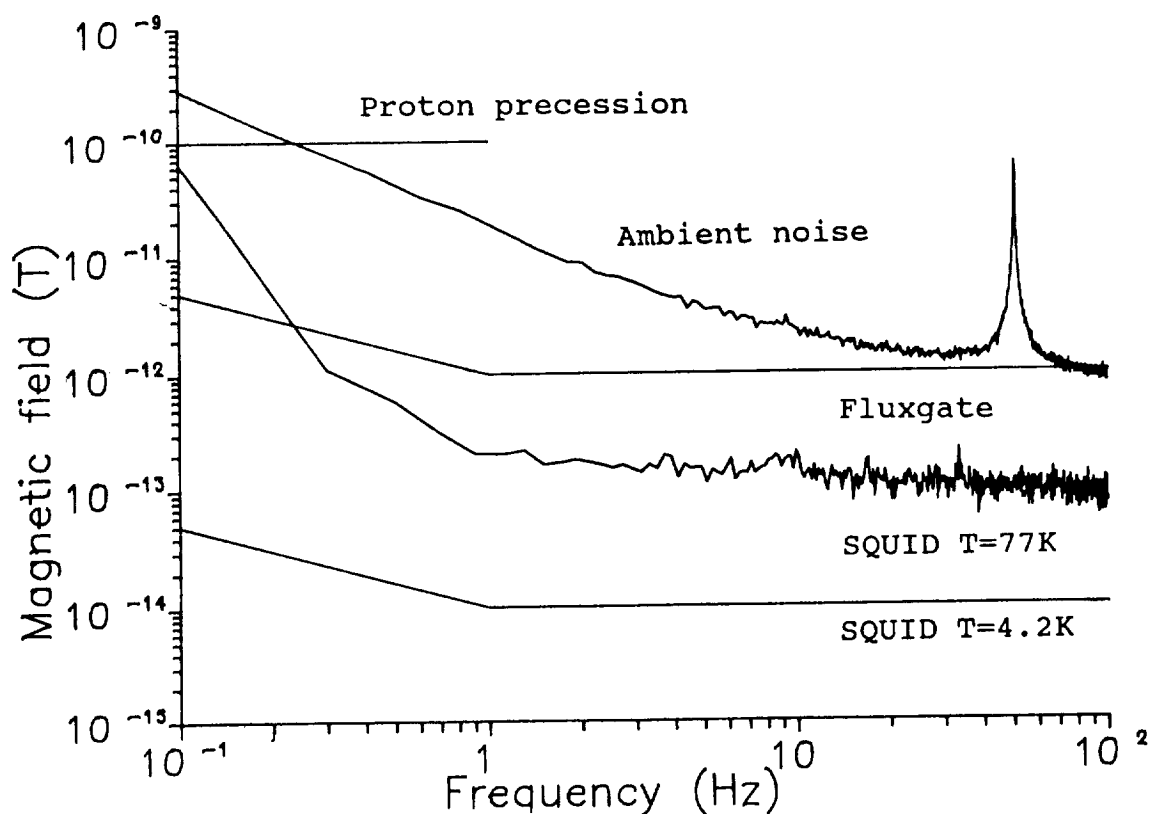
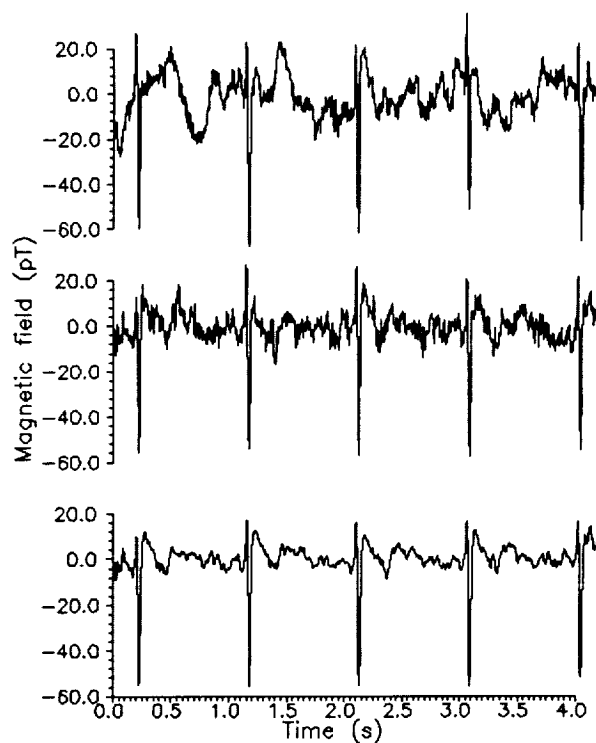


Fig.3.

In fig.3 the ambient noise spectrum is depicted (upper curve), which was read at night at a distance of 20m from the nearest Laboratory building in Dubna. It is clearly seen, that the ambient noise is considerably higher than the squid self-noise. Thus, we can suppose that such a magnetometer can be used for geophysical investigations.

One of the most interesting fields of the squid-based magnetometer application is biomagnetism, particularly, the human heart magnetocardiogram measuring. The low-temperature squids for a long time have been used in this area and to the present moment many interesting and important scientific results have been obtained.

In fig.4 a magnetocardiogram is shown, which was recorded by the above described magnetometer in a bandwidth of 60Hz (upper curve). The magnetocardiogram was taken in an aluminium box (~5mm wall) within 50m from the nearest Laboratory building.



*Fig.4.*

As a sensitive element, as mentioned before, one-hole squid was operating. The squid inside the sealed copper thinwall container was placed on the bottom of the biomagnetic nitrogen cryostat. The squid was placed ~25mm above the human chest.

The observations have shown that the main noise contribution was not due to the squid but to the Earth's magnetic field variations, industrial inductions and mainly to the vibrations caused by liquid nitrogen boiling and by vibrations of the box. Further attempts in our work are needed in view to reduce the magnetic noise inductions. Nevertheless, the estimations promise us the maximum signal/noise relation of the high- $T_c$  squid-magnetocardiometer to be (at the MCG amplitude - 20pT) not less than 10:1 in a bandwidth of 60Hz. Apparently, such resolution would be enough not only for steady cardiogram reading but even for thin structure investigation at average technique application.

When this paper was ready a new magnetocardiogram was measured with two high-temperature one-hole squids. In fig.4 (middle curve) a MCG in a real scale of time in a bandwidth of 60 Hz, and the same magnetocardiogram after four period average (lower curve) are given.

